Audio-magnetotelluric investigation of geothermal systems in the Mount Meager Volcanic Complex, southwestern Canada

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MTNet EMinar
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Natural Resources Canada
Ressources naturelles Canada
Canada
Geoscience BC
CARLETON UNIVERSITY
EARTH SCIENCES

Outline

1. Introduction
2. Mount Meager Volcanic Complex
3. Electrical resistivity structures
4. Petrophysical properties and conceptual model
5. Conclusions

What is Geothermal Energy?

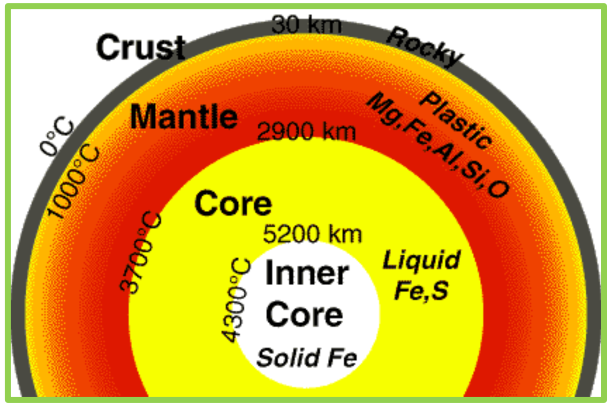
Geothermal = “geo” + “thermos”

- Renewable source of energy derived from heat produced in the subsurface.

  1- Thermal anomaly

  2- Accessible depth by drilling wells

  3- Sufficient porosity and permeability

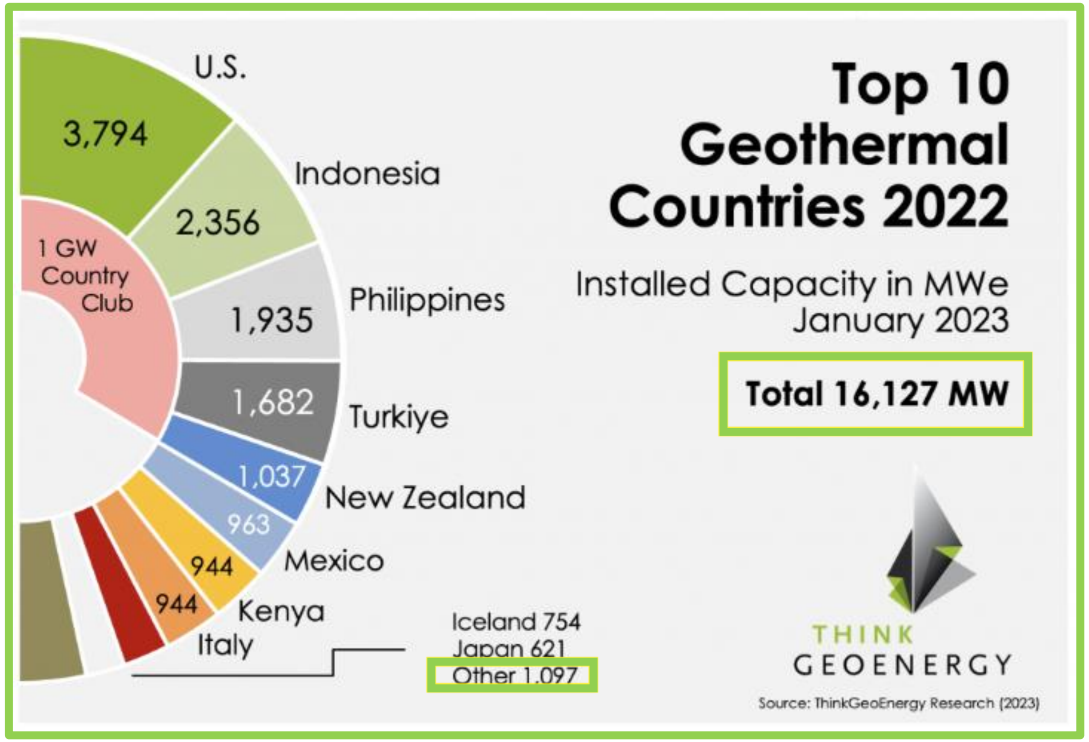


Arizona.edu

	Muffler (°C)	Hochstein (°C)	Benderitter and Cormy (°C)
Low enthalpy	< 90	< 125	< 100
Moderate enthalpy	90 – 150	125 – 225	100 – 200
High enthalpy	> 150	> 225	> 200

Geothermal Energy in the World

- 28 countries produce power with geothermal resources.
- 10 countries has 93.2 % of the world's installed capacity for power generation.
- 5 countries with higher than 1 GW installed capacity for power generation.



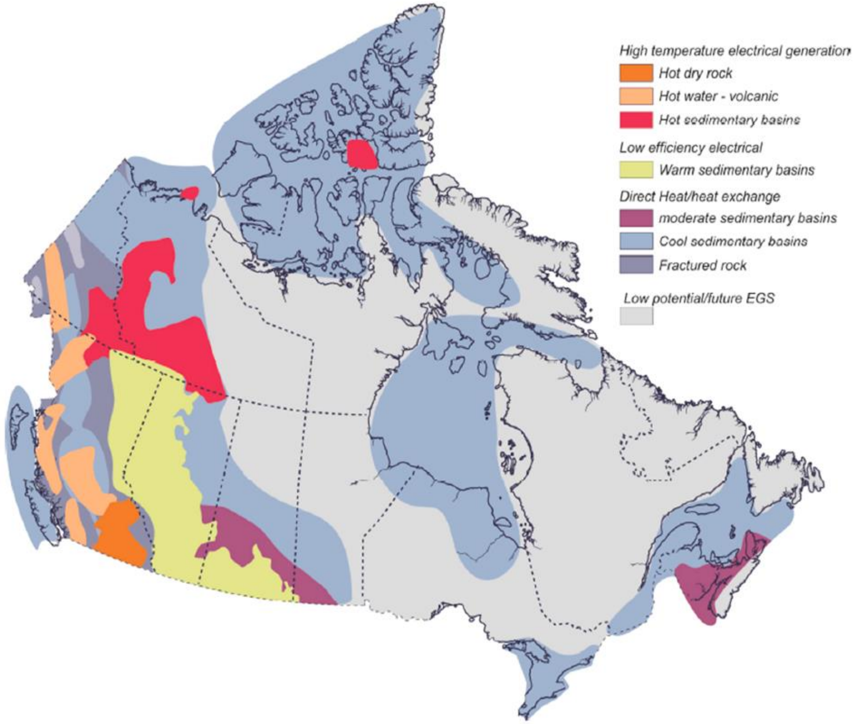
Think GeoEnergy (2023)

Geothermal Energy in Canada

Geothermal resources in Canada is still under study.

High potential to produce power by geothermal energy:

- British Columbia
- Northern Territories
- Yukon
- Alberta and Saskatchewan

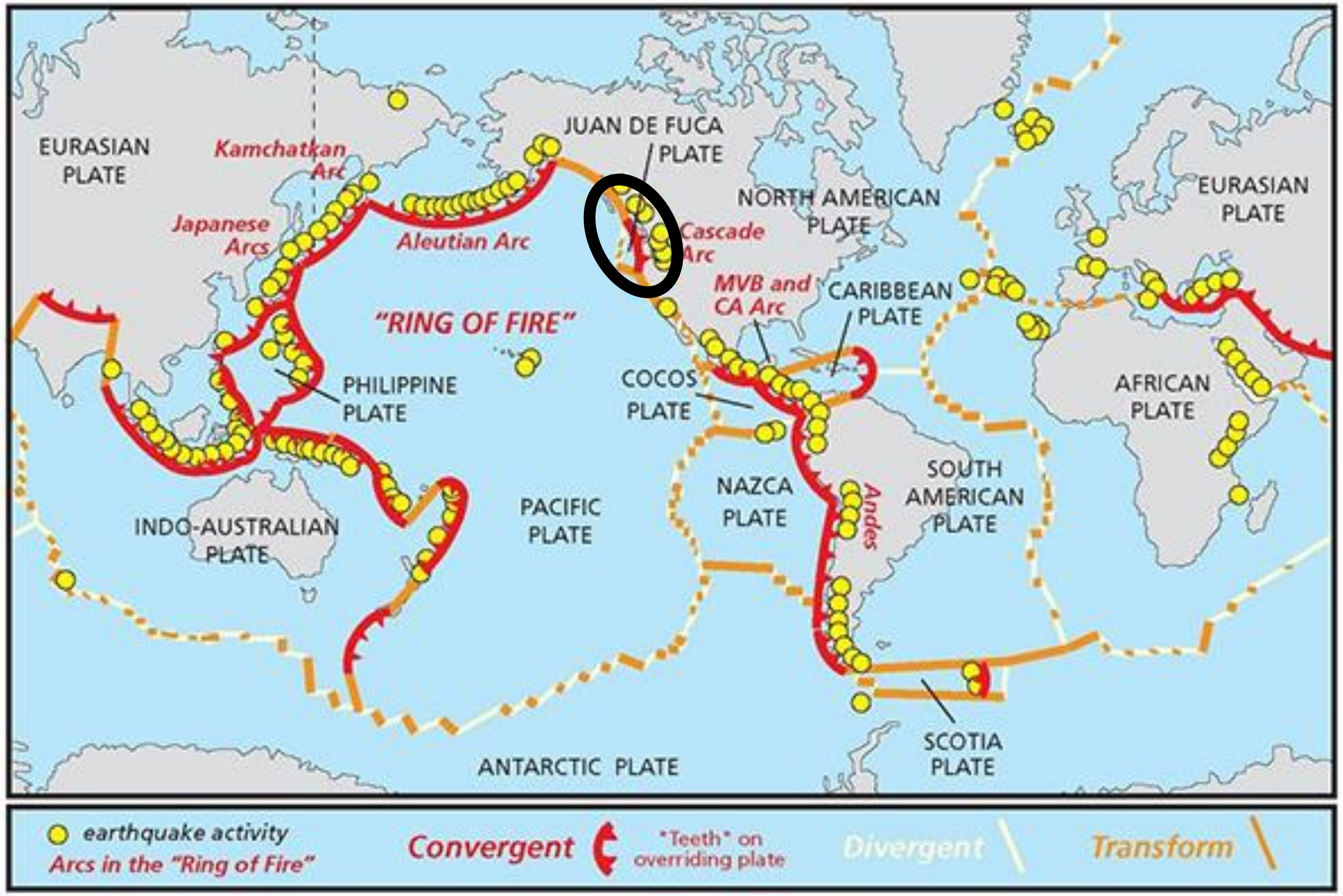


Grasby et al. (2012)

Study Area

Garibaldi Volcanic Belt

- Located along the Ring of Fire



National Parks Service (Public Domain)

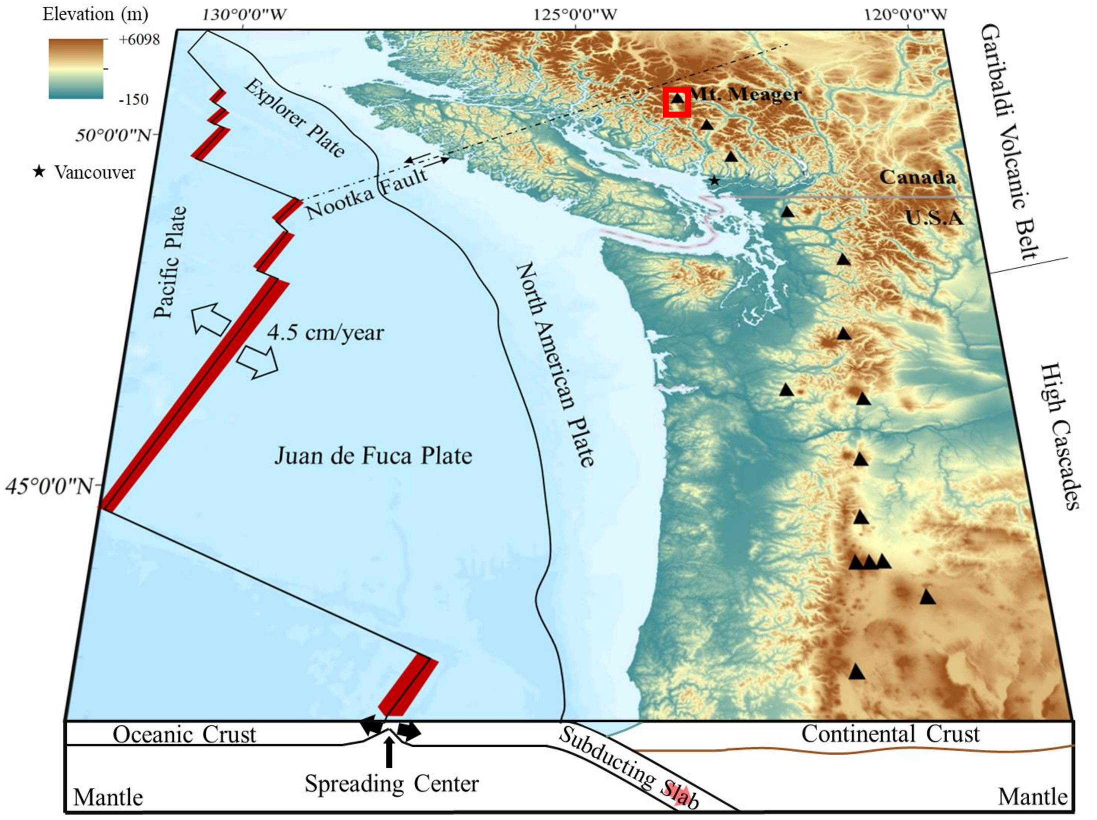
Study Area

Garibaldi Volcanic Belt

- Located along the Ring of Fire

- The Garibaldi Volcanic Belt represents a chain of young volcanoes in SW BC.

- It is known to have abundant thermal springs and volcanic structures including Mount Garibaldi and Mount Meager Volcanic Complex.



Study Area

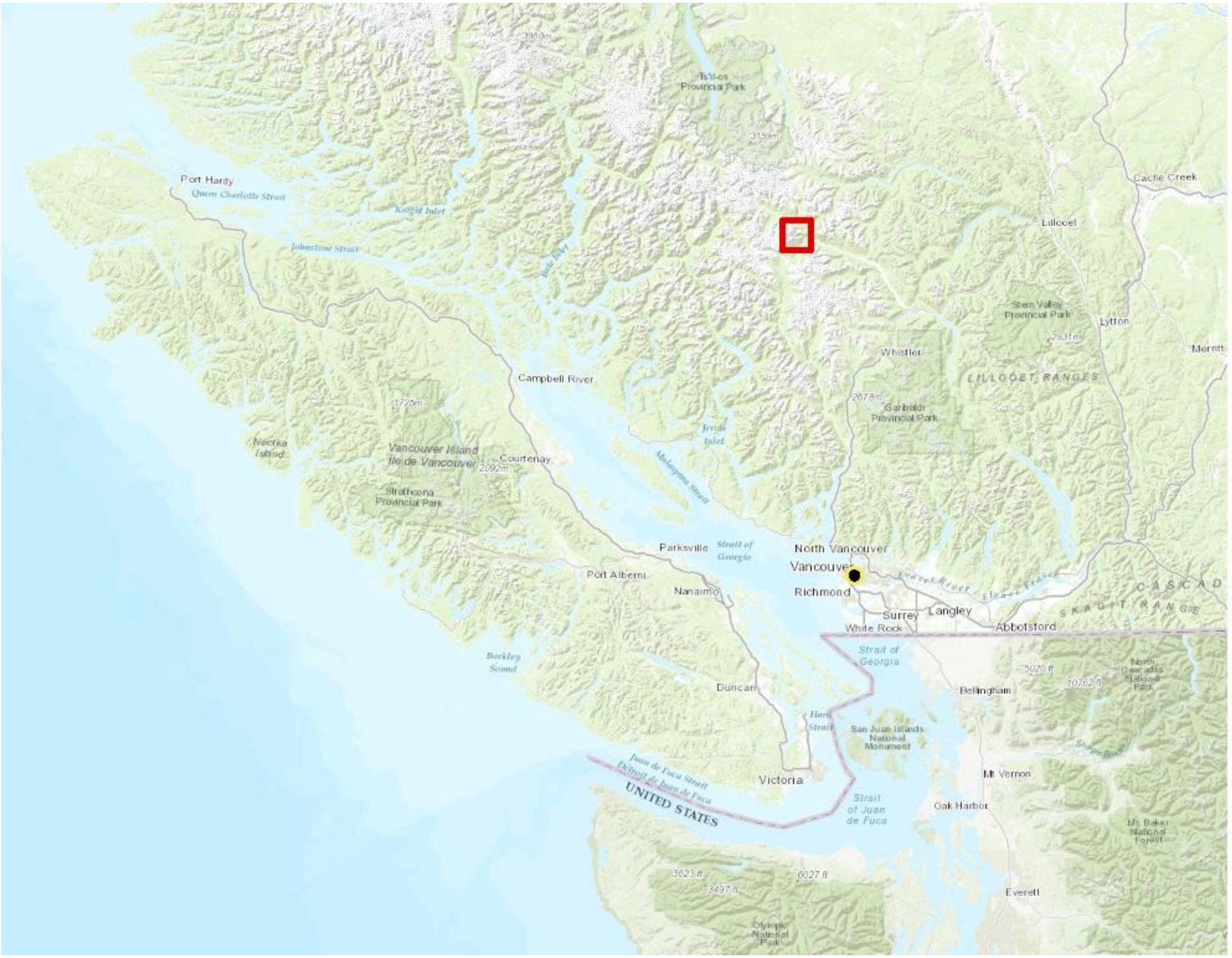
Mount Meager Volcanic Complex

Structures:

- Meager Creek Fault
- No-Good Discontinuity
- Camp Fault
- Carbonate Fault

Springs:

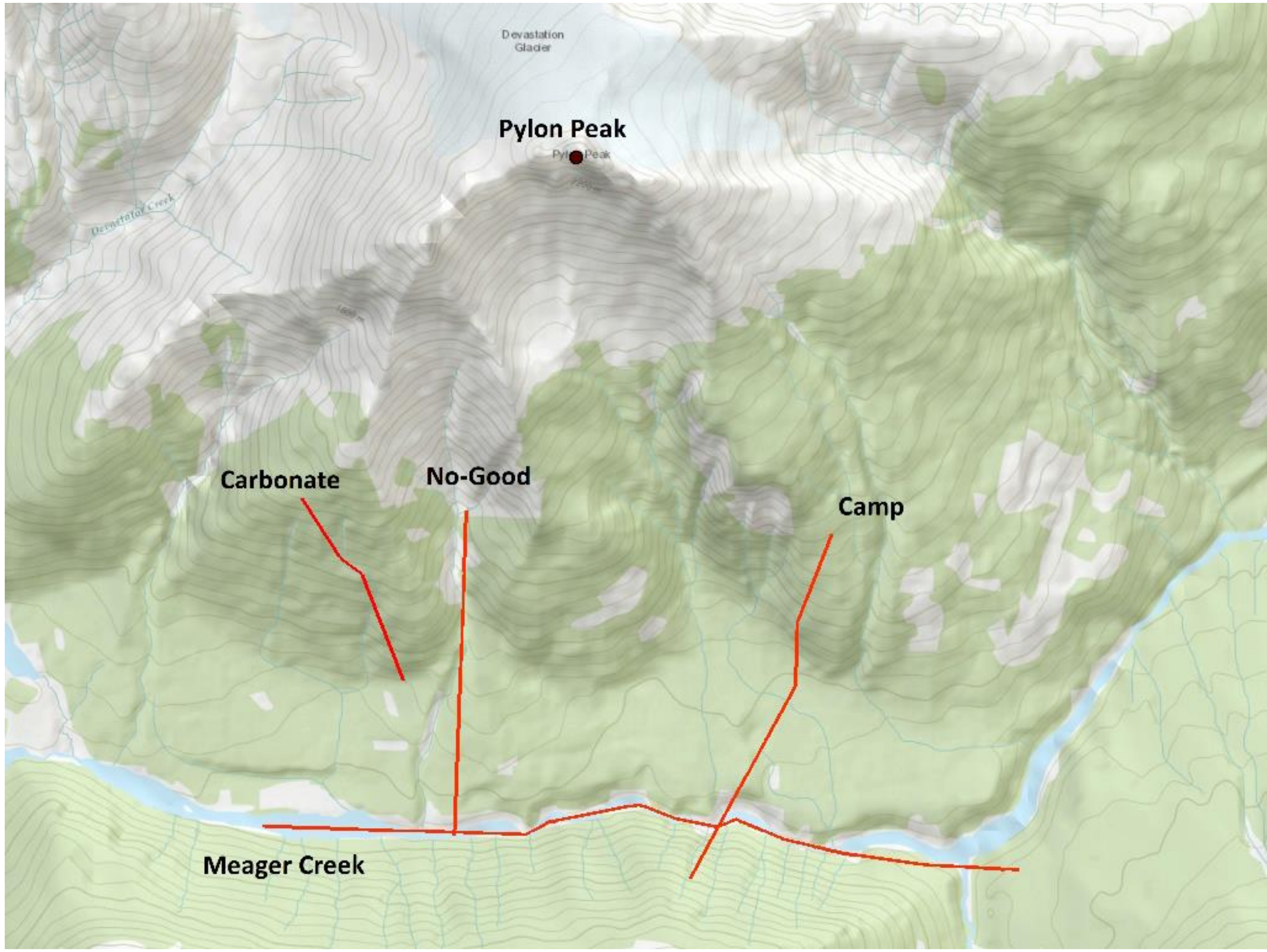
- Meager hot spring (30° - 59°C)
- Placid hot spring (45 °C)
- No-Good warm spring (30 - 40°C)



Motivation

Mount Meager Volcanic Complex has been studied since the 1970s.

- Multidisciplinary data (Reports in Geoscience BC website)
- Existence of warm and hot springs and drilled boreholes
- Boreholes showed area with high temperature anomalies.
- Proximity to large human settlements

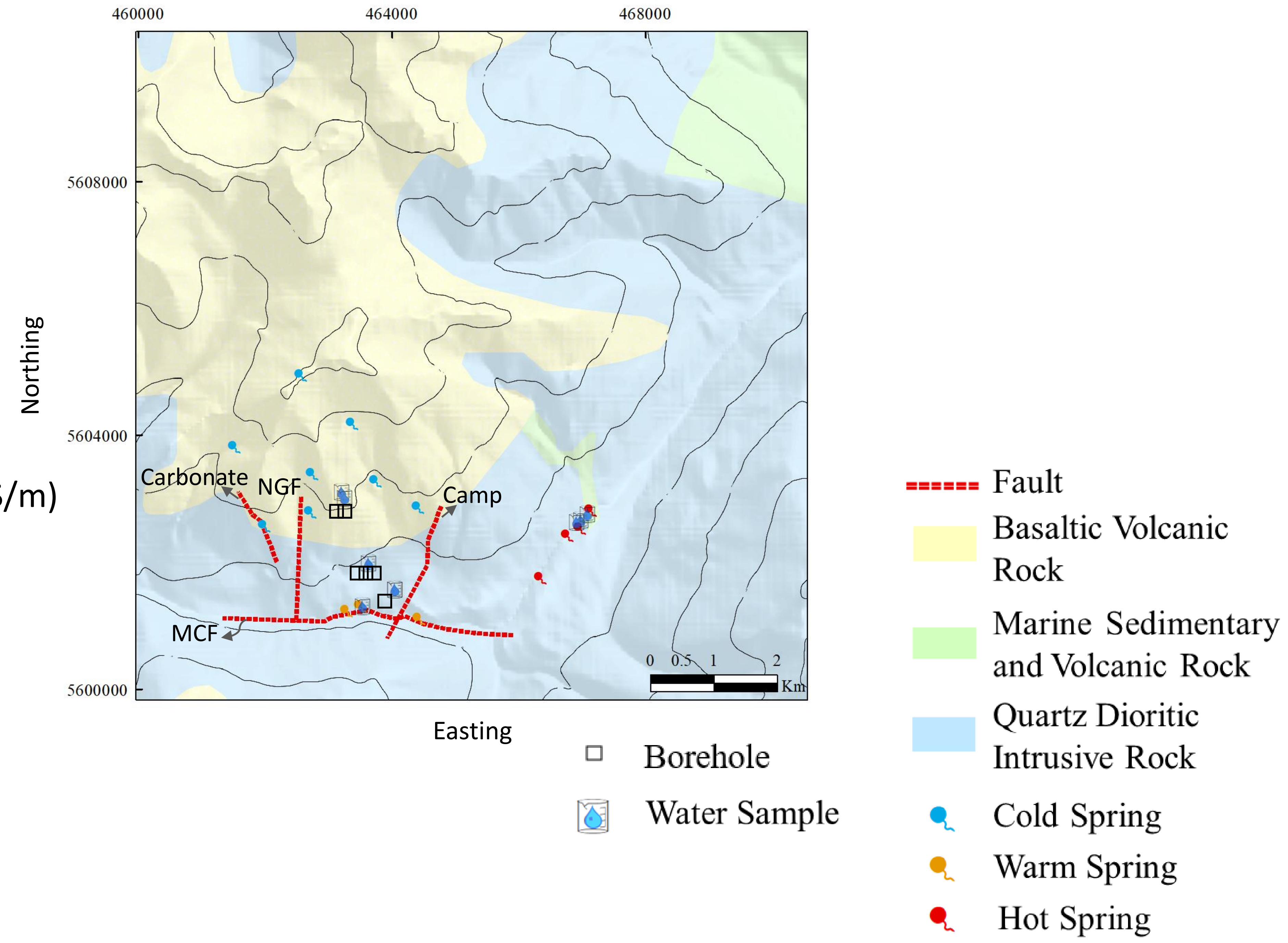


Data

Water Chemistry

Measurements:

- Salinity (ppm)
- Electrical conductivity (S/m)
- pH



Data

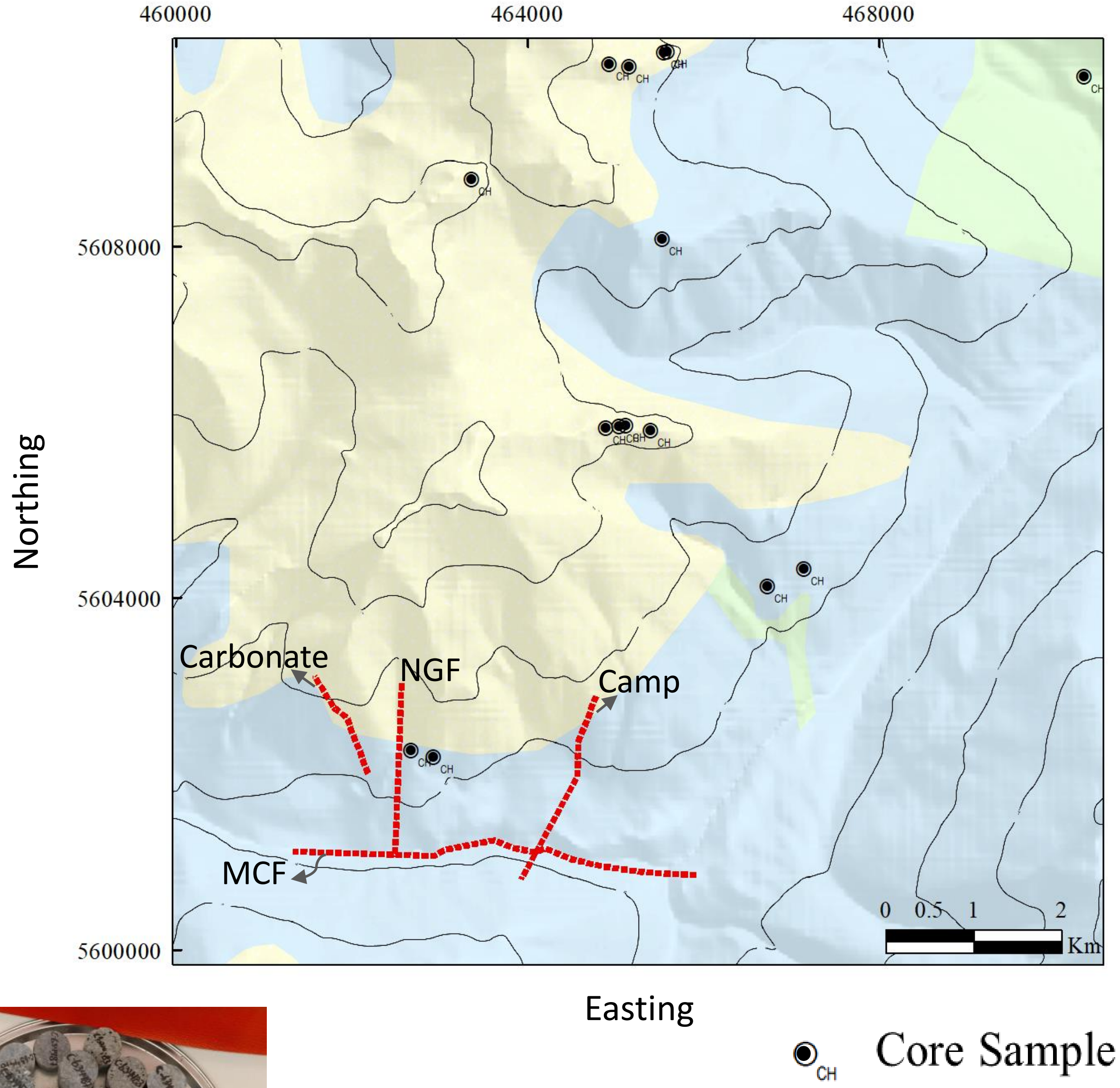
Rock Samples

Core samples:

Volcanic and intrusive rocks

Measurements:

- Porosity
- Permeability

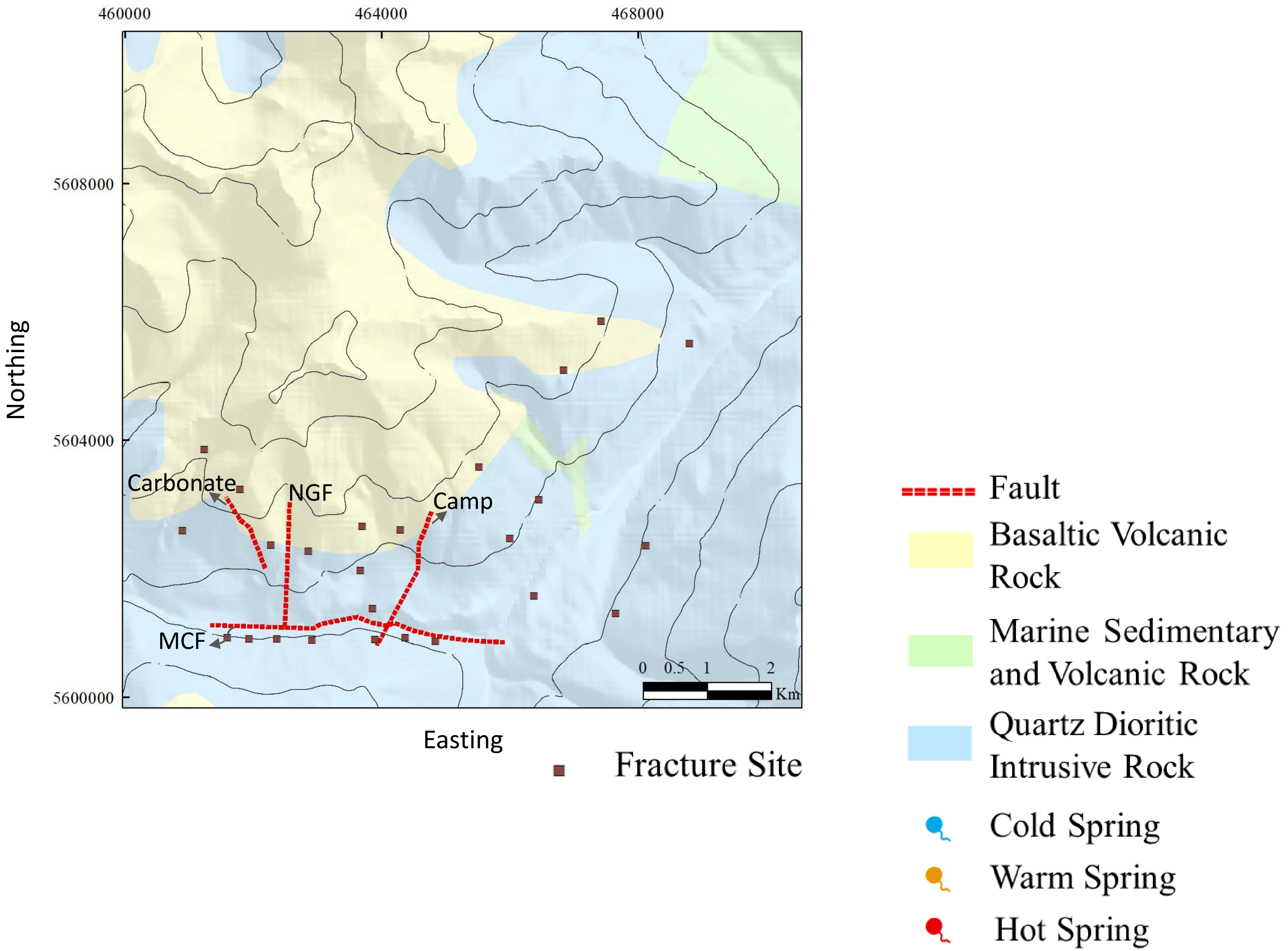


Data

Fracture Data

Measurements:

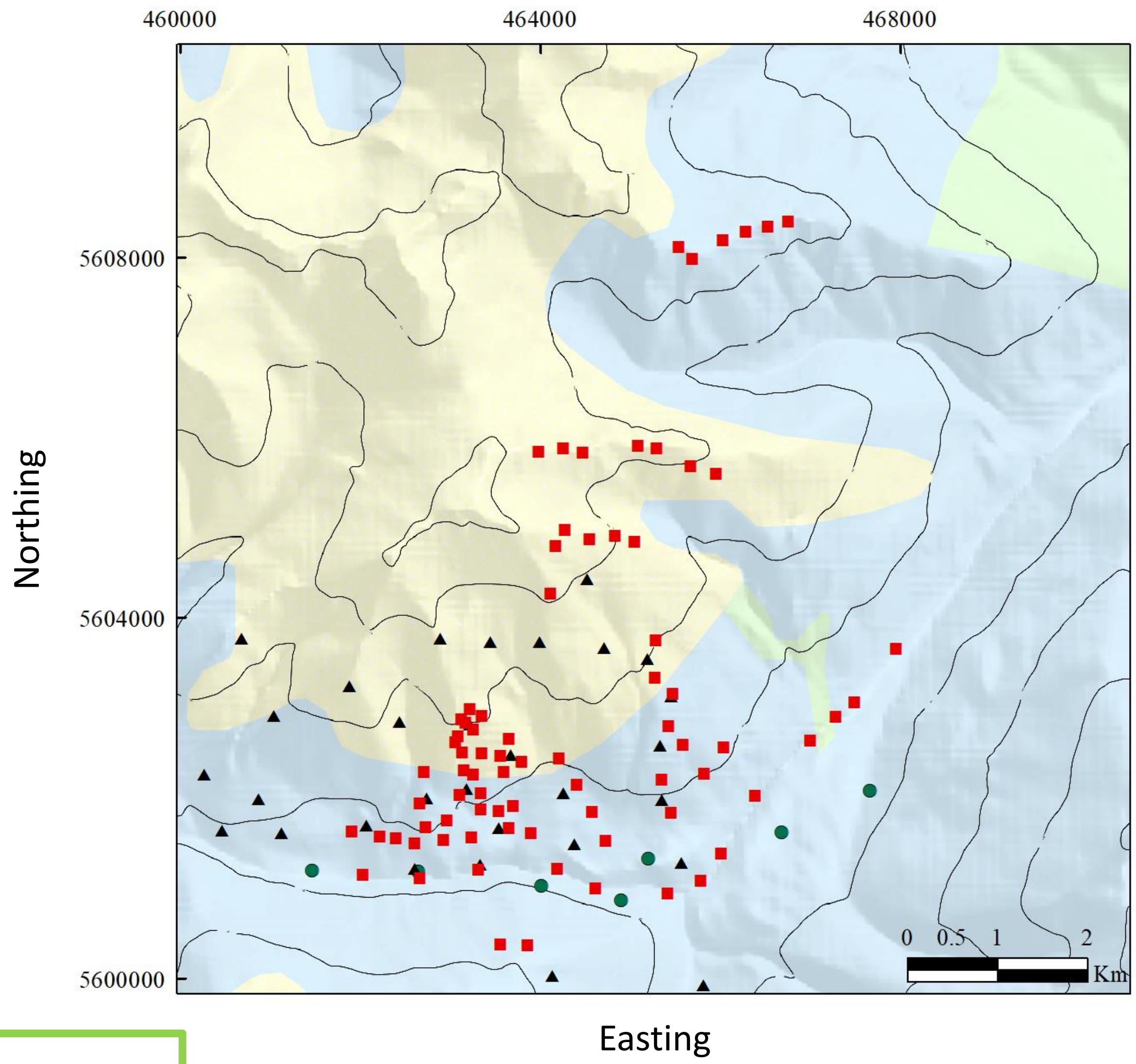
- Spacing (m)
- Aperture (mm)

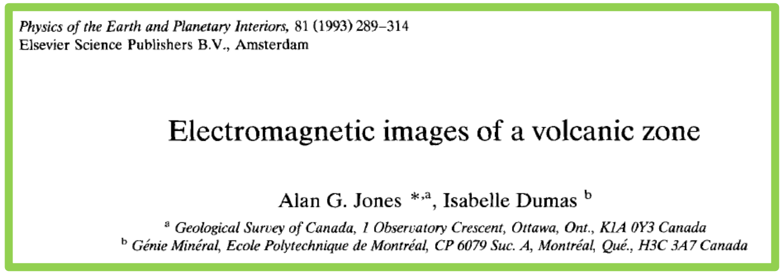


Data

Magnetotellurics (MT)

- Legacy MT data-1982
- Frontier MT data-2001
- AMT data-2019




Physics of the Earth and Planetary Interiors, 81 (1993) 289–314
Elsevier Science Publishers B.V., Amsterdam

Electromagnetic images of a volcanic zone

Alan G. Jones *,[a], Isabelle Dumas [b]

[a] *Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ont., K1A 0Y3 Canada*
[b] *Génie Minéral, Ecole Polytechnique de Montréal, CP 6079 Suc. A, Montréal, Qué., H3C 3A7 Canada*

Model representation

Data

AMT and MT stations (107 stations and 34 periods).

Impedance tensor of data (0.01 Hz–10000 Hz), with 5% error floor.

3D Model

Vertical mesh: 40 m layers for topography

Subsequent layers increased by a factor of 1.12.

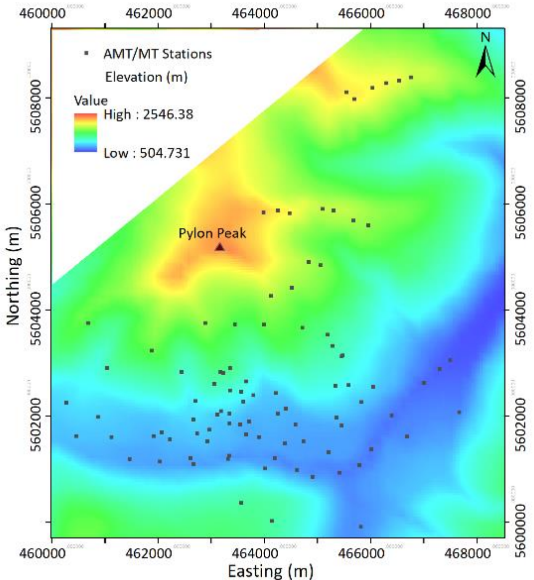
Horizontal mesh: 75 m x 75 m cells

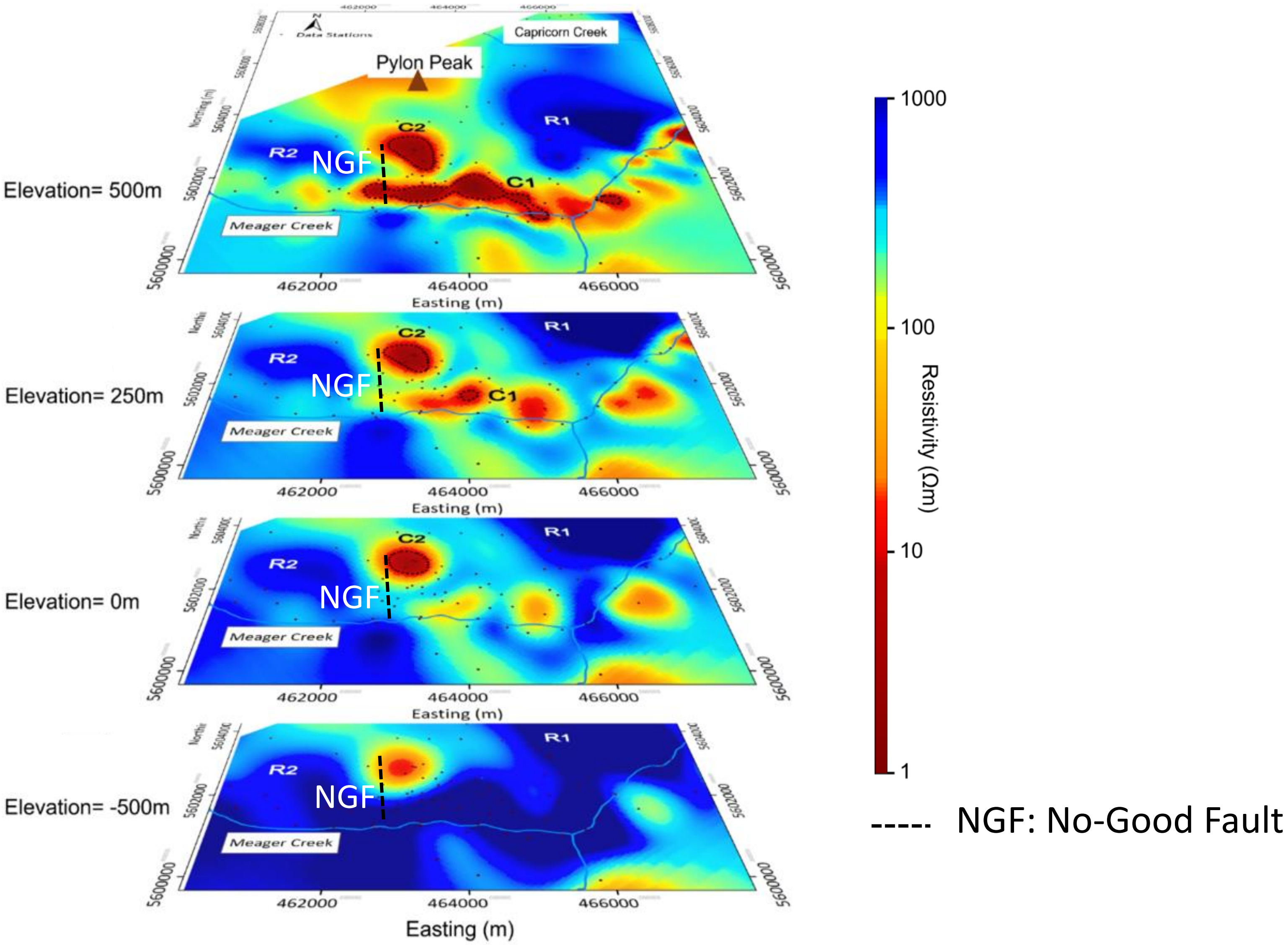
Padding cells increasing by a factor of 1.2.

Starting model: 300 Ωm half-space

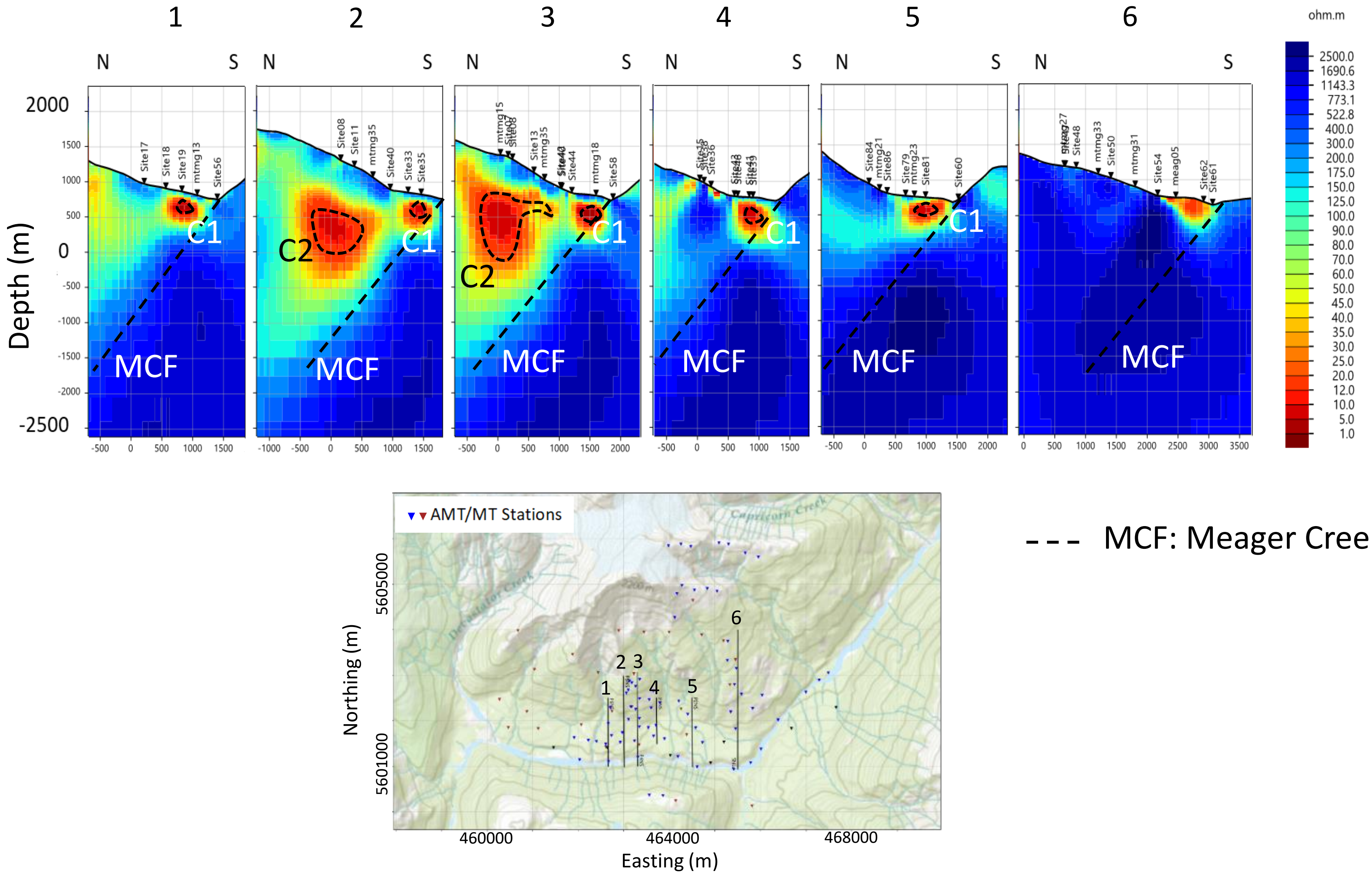
Total final RMS misfit: 1.3

Resistivity Model: Horizontal Plan View



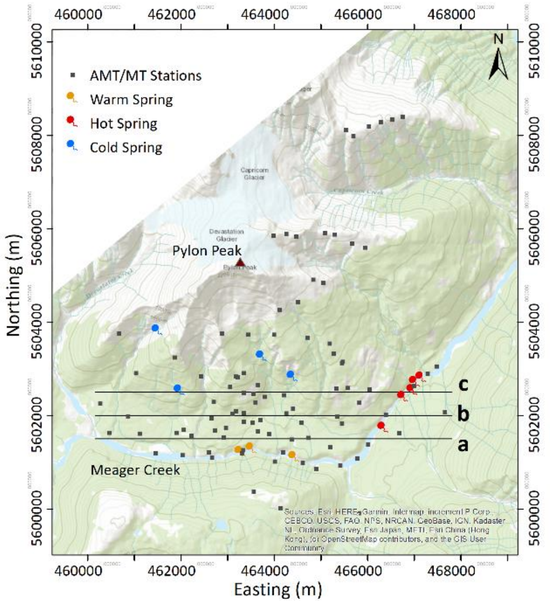


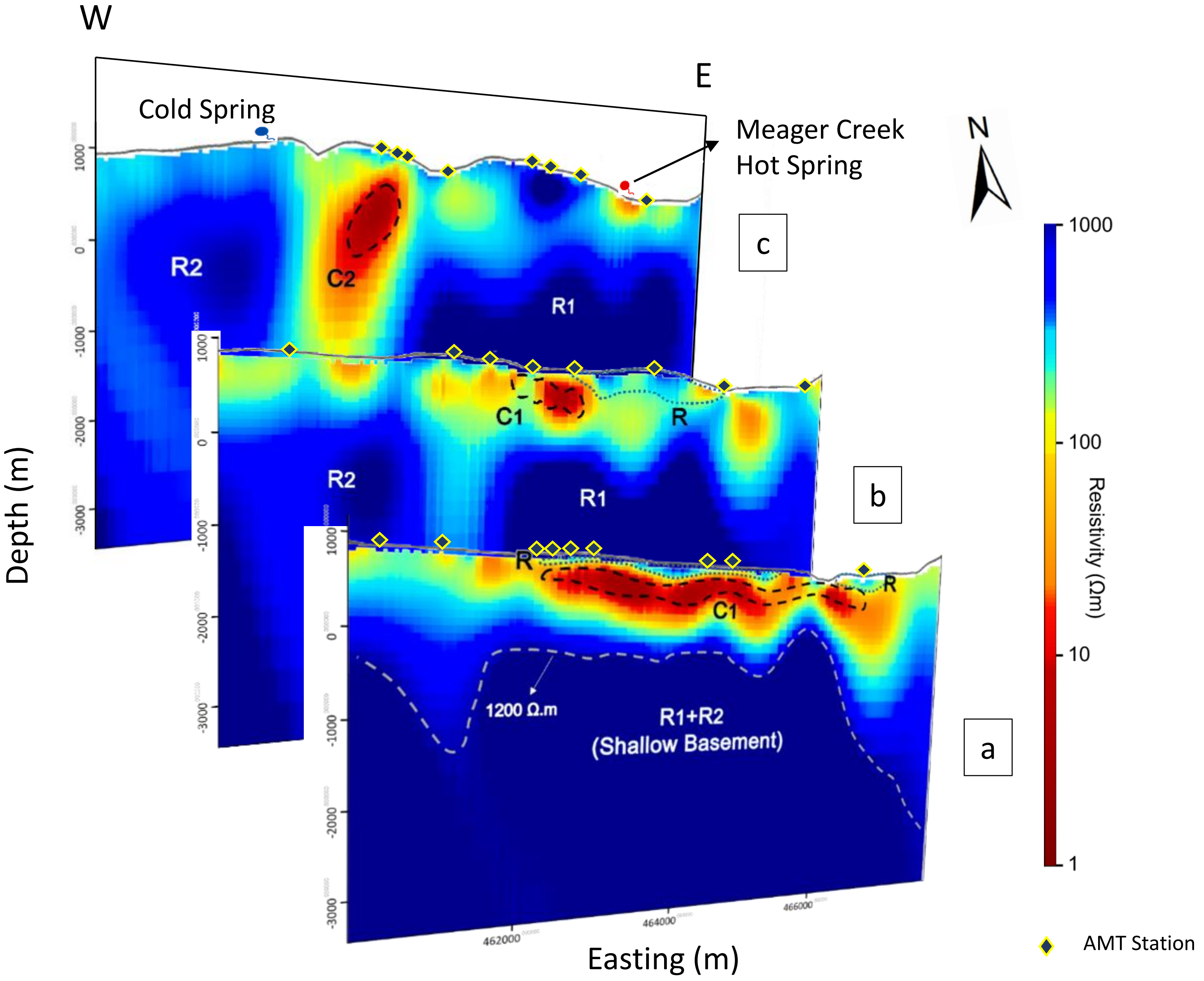
Resistivity Model: North-South Cross-Sectional Views



--- MCF: Meager Creek Fault

Resistivity Model: East-West Cross-Sectional Views





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- ✓ Mount Meager Volcanic Complex
- ✓ Electrical resistivity structures

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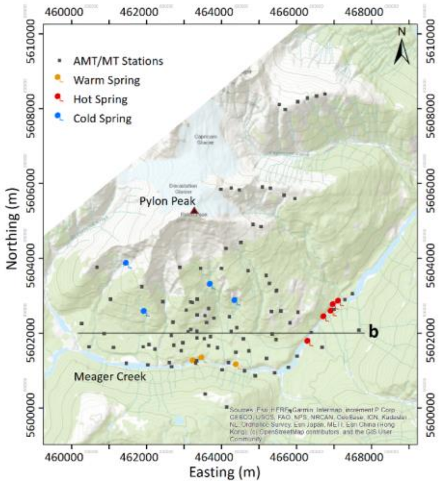
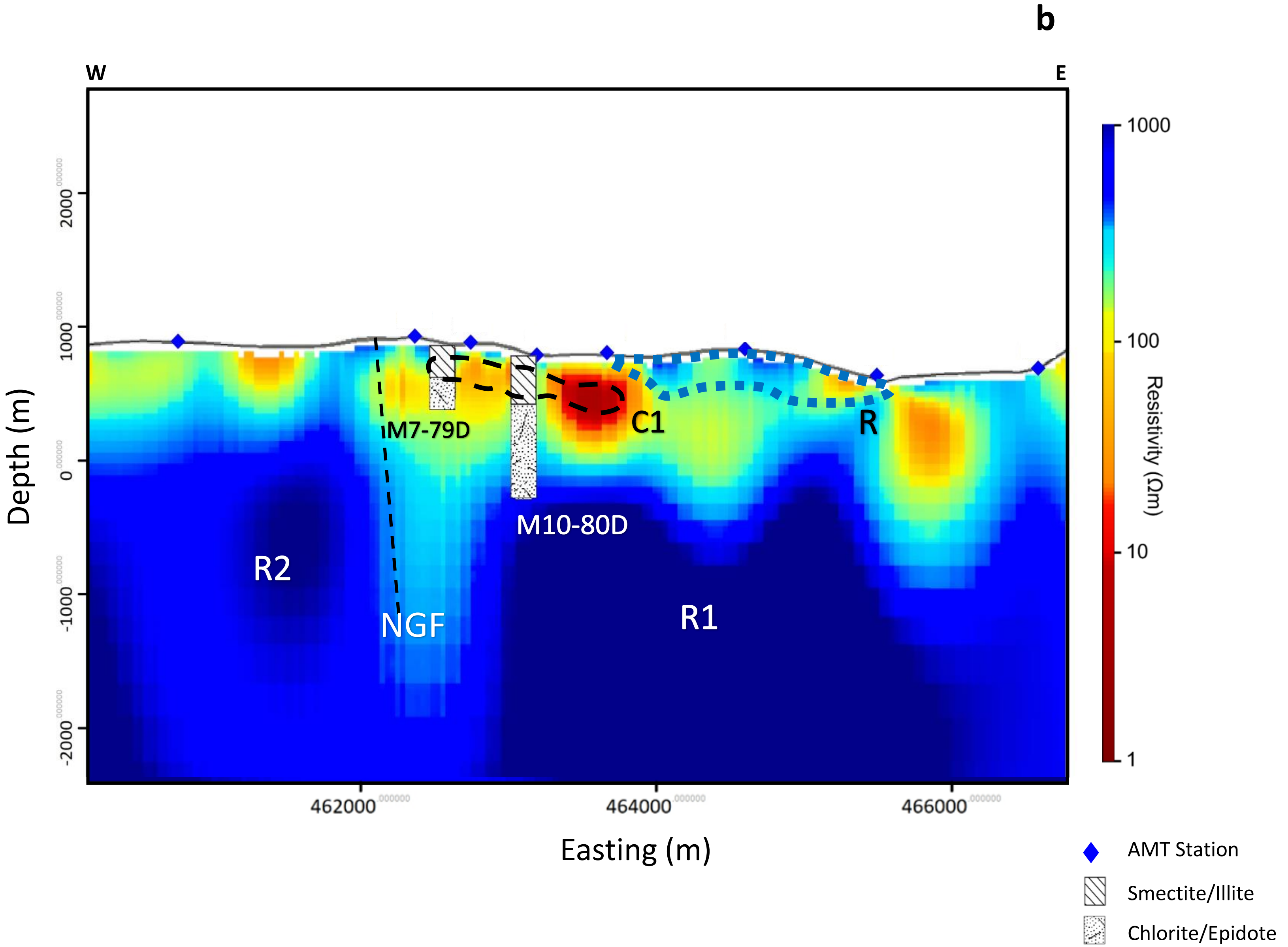
5. Conclusions

Geology

- Geological logs
- Temperature data





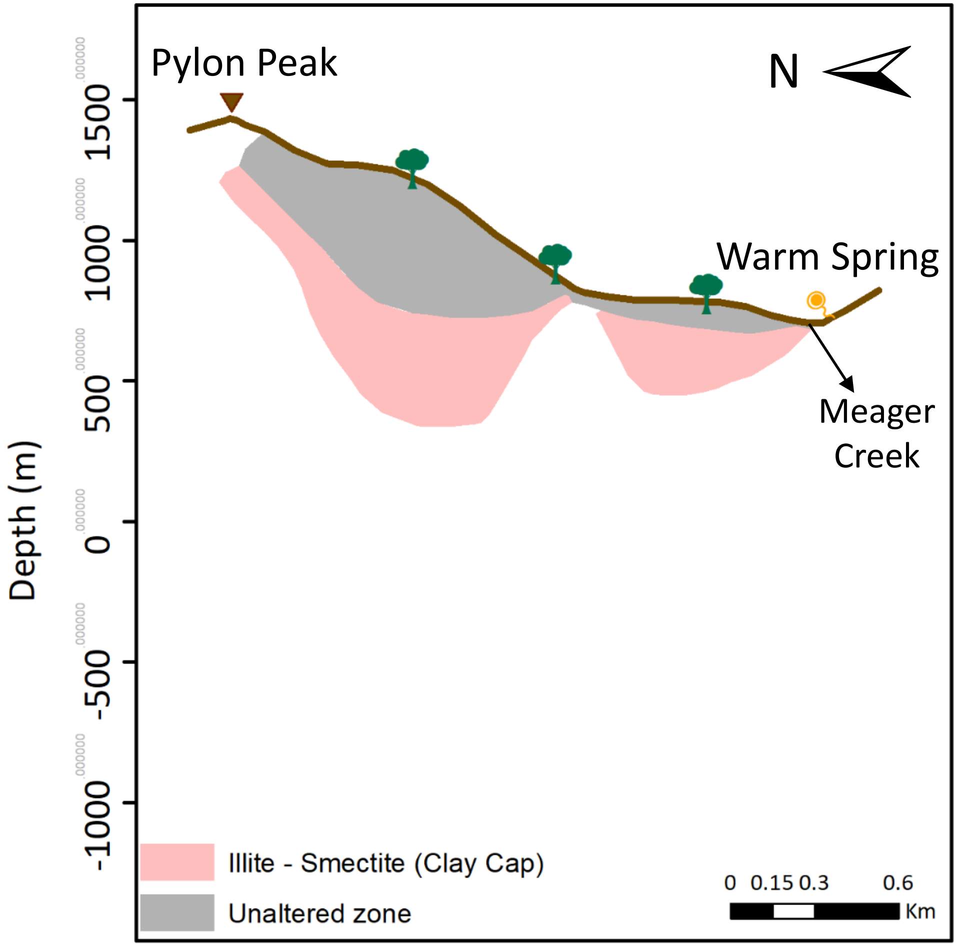
Building a Conceptual Model

The MMVC geothermal field:

Geological logs

AMT model

Temperature data



(Not to scale)

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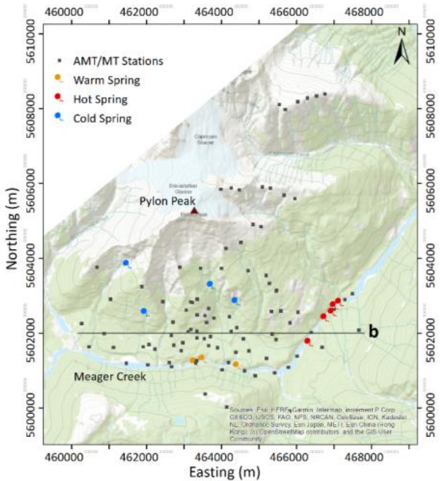

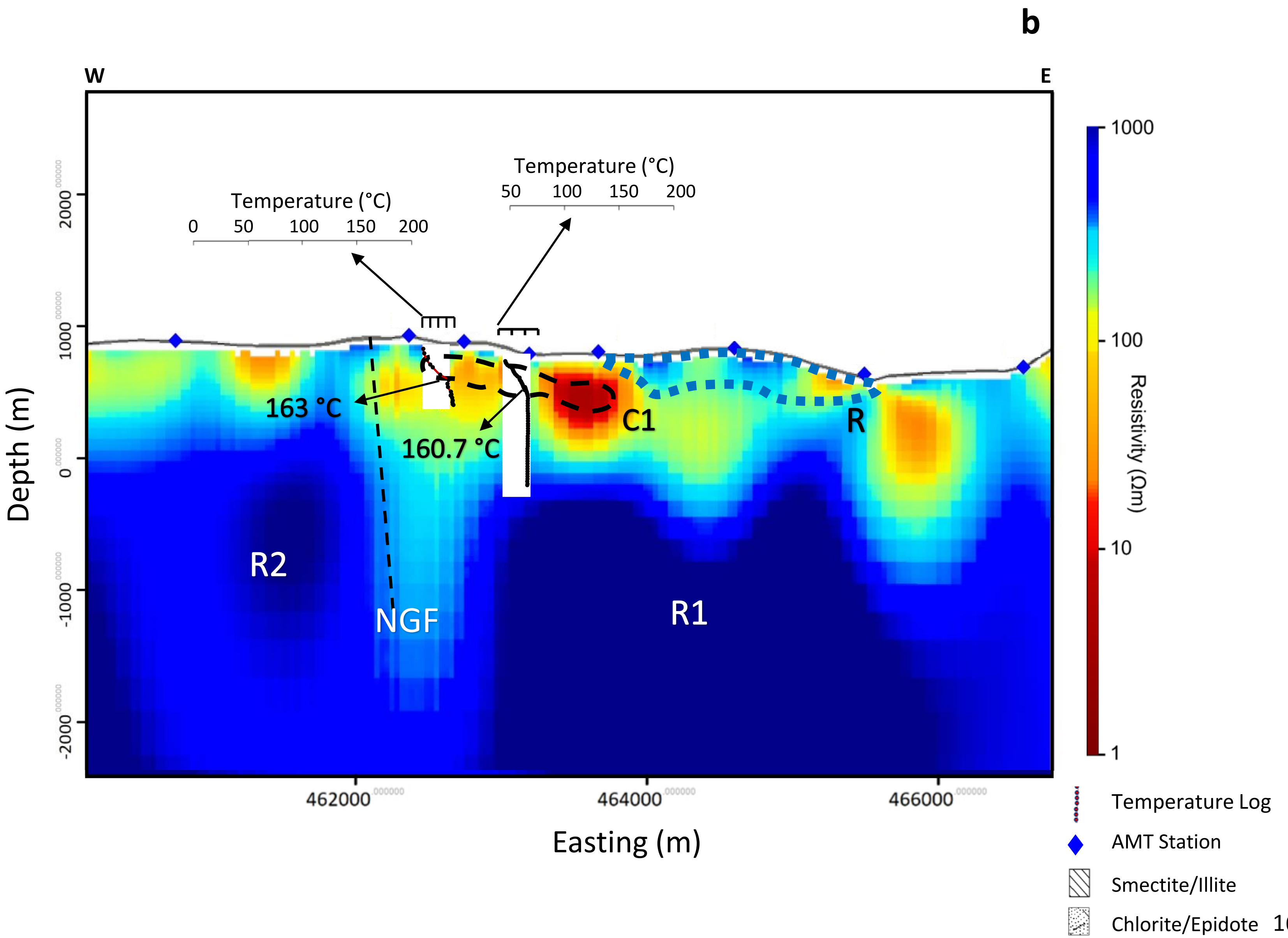

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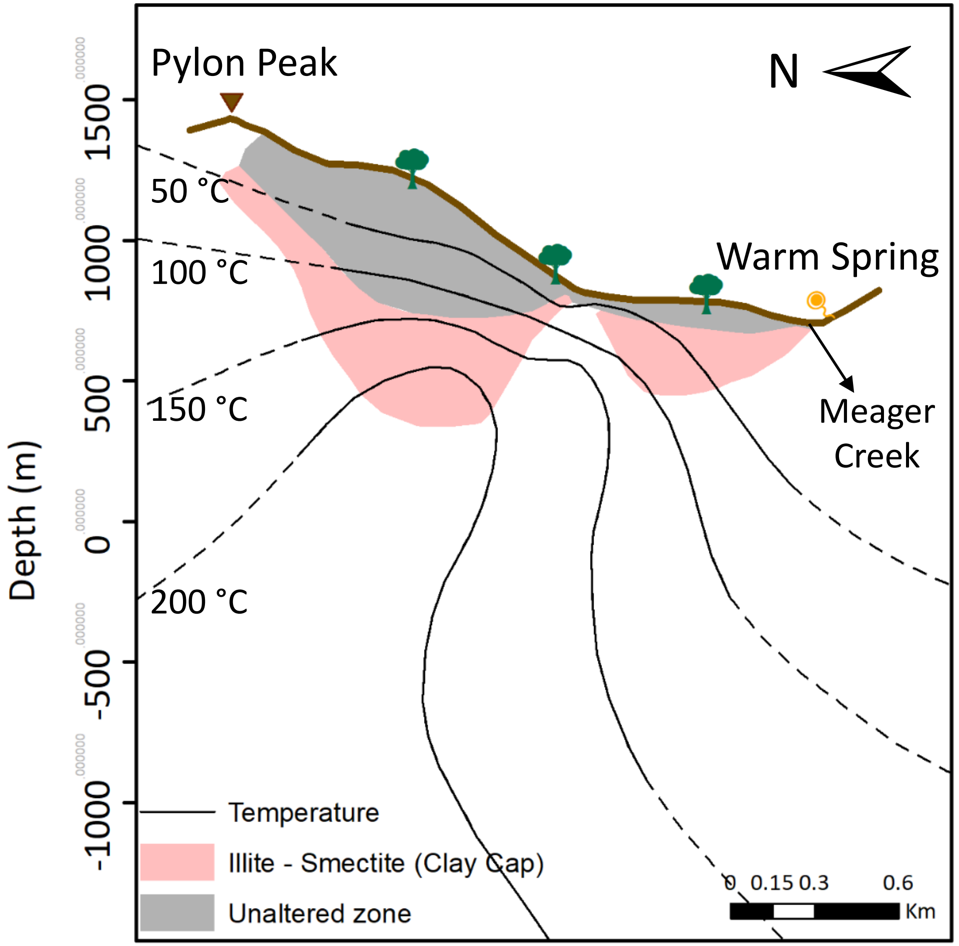


(Not to scale)

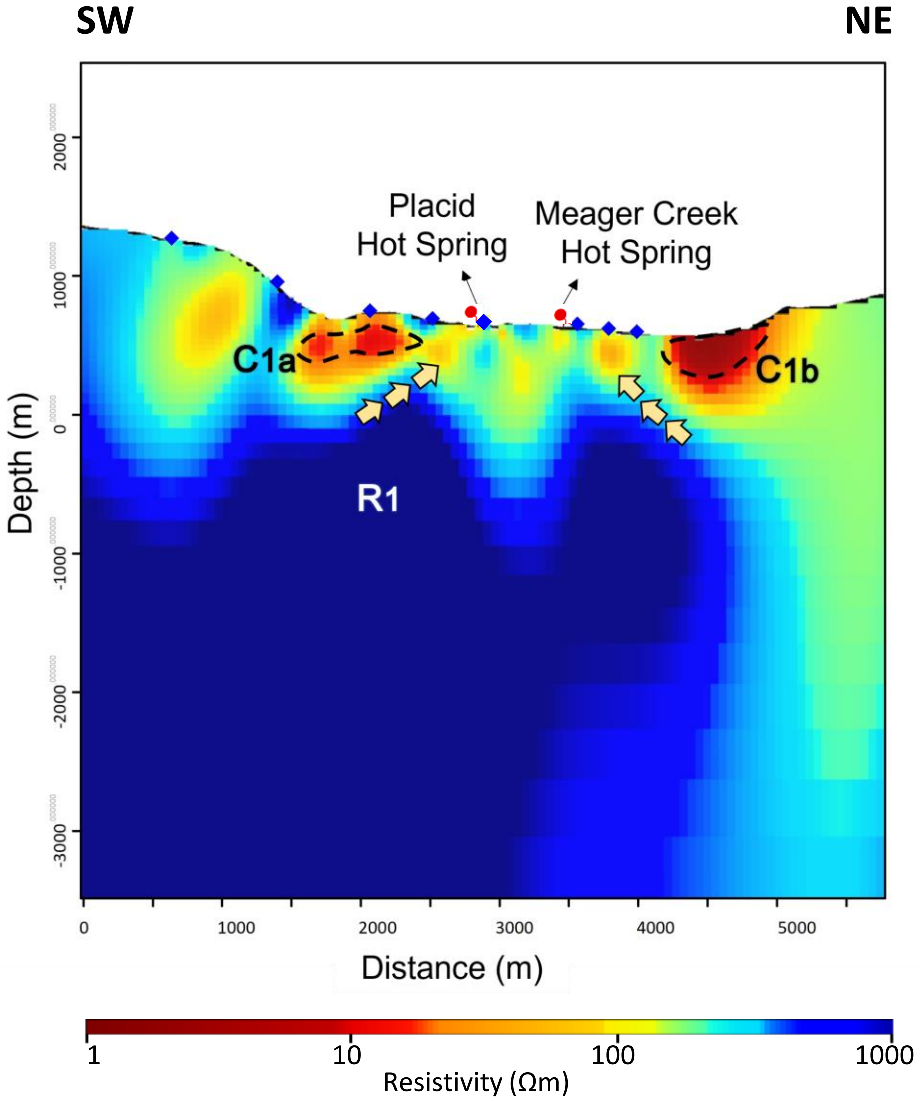
Petrophysical Model

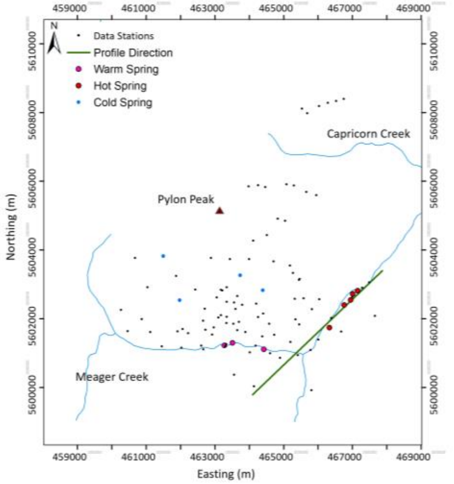
Fluid Flow Pathways

Fluid fraction:

- Zones with higher porosity
- Possible size of the resource

The average electrical resistivity of the pathways in the AMT model is from 40 to 300 Ωm.





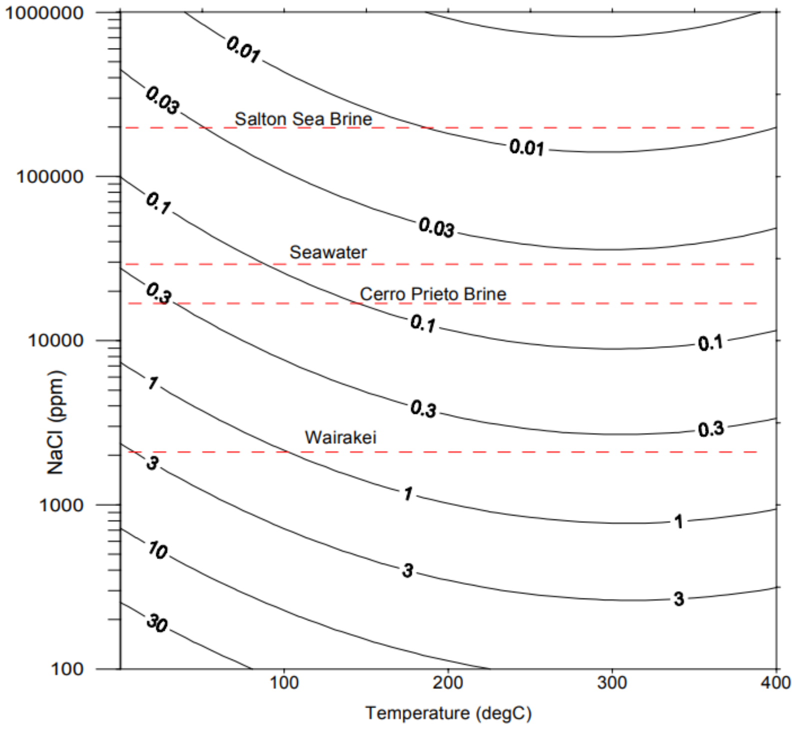
Petrophysical Model

Fluid Resistivity

$\boldsymbol{\rho_f}$

Known Relationship: $\rho_f = 0.0123 + \left(\frac{1}{2.74 \times 10^{-4} \times C_{sp}^{0.955}}\right)$ **(Source: Tiab & Donaldson, 2016)**

Charts:

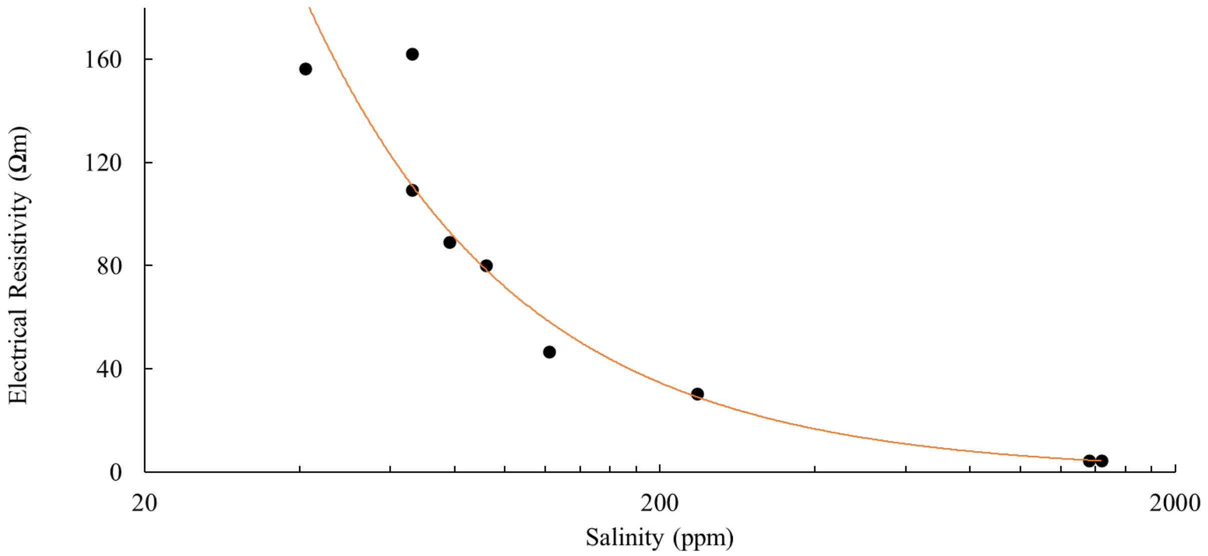


Ussher et al. (2000)

Petrophysical Model

Fluid Resistivity

Meager Fluid Chemistry Data: $\rho_f = \left(\frac{1}{1.1 \times 10^{-4} \times C_{sp}^{1.051}}\right)$



Petrophysical Model

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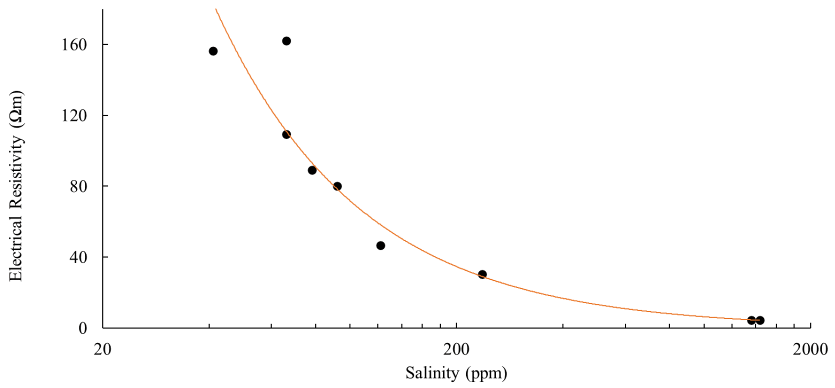


Temperature Correction:

$$R_{wT_2} = R_{wT_1} \left(\frac{T_1 + X}{T_2 + X} \right)$$

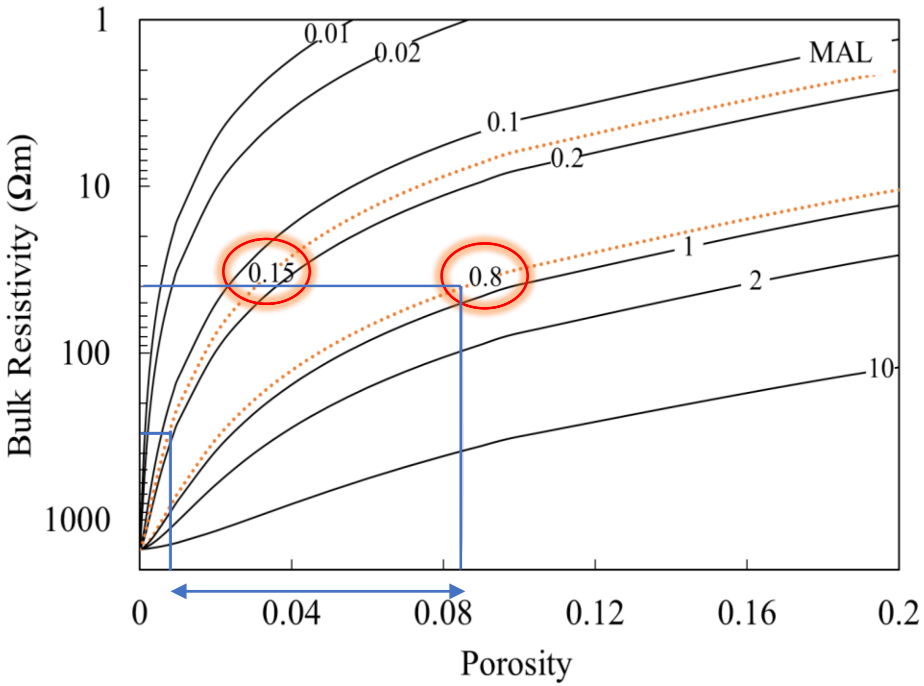
$$X = 10^{-\left(\left(0.3404 \times \log_{10} R_{wT_1}\right) - 0.6414\right)}$$

ρ_f: 0.15-0.8 Ω.m

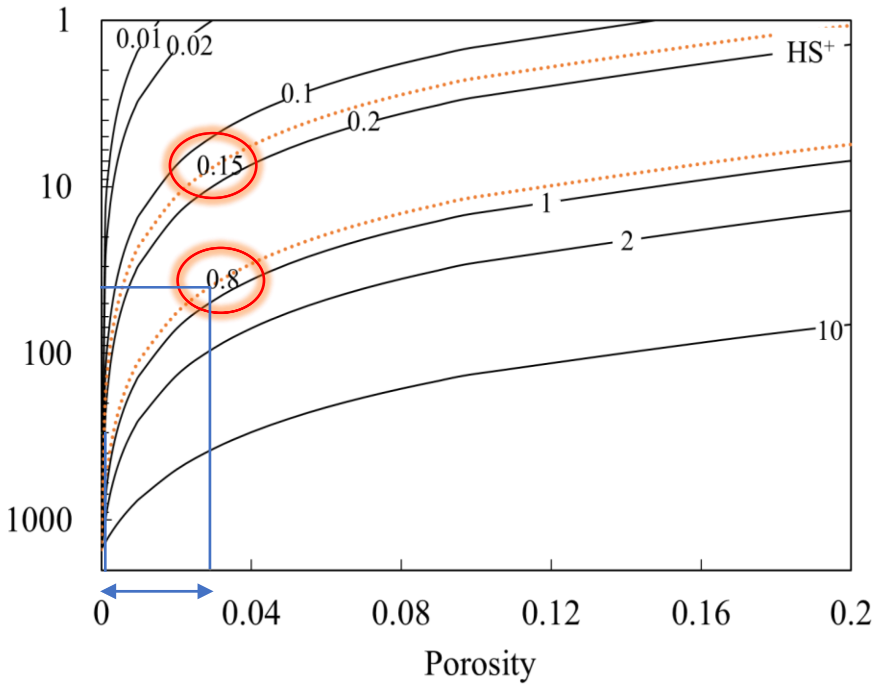
Petrophysical Model

Fluid Flow Pathways

Modified Archie’s Law



Hashin and Shtrikman upper bound



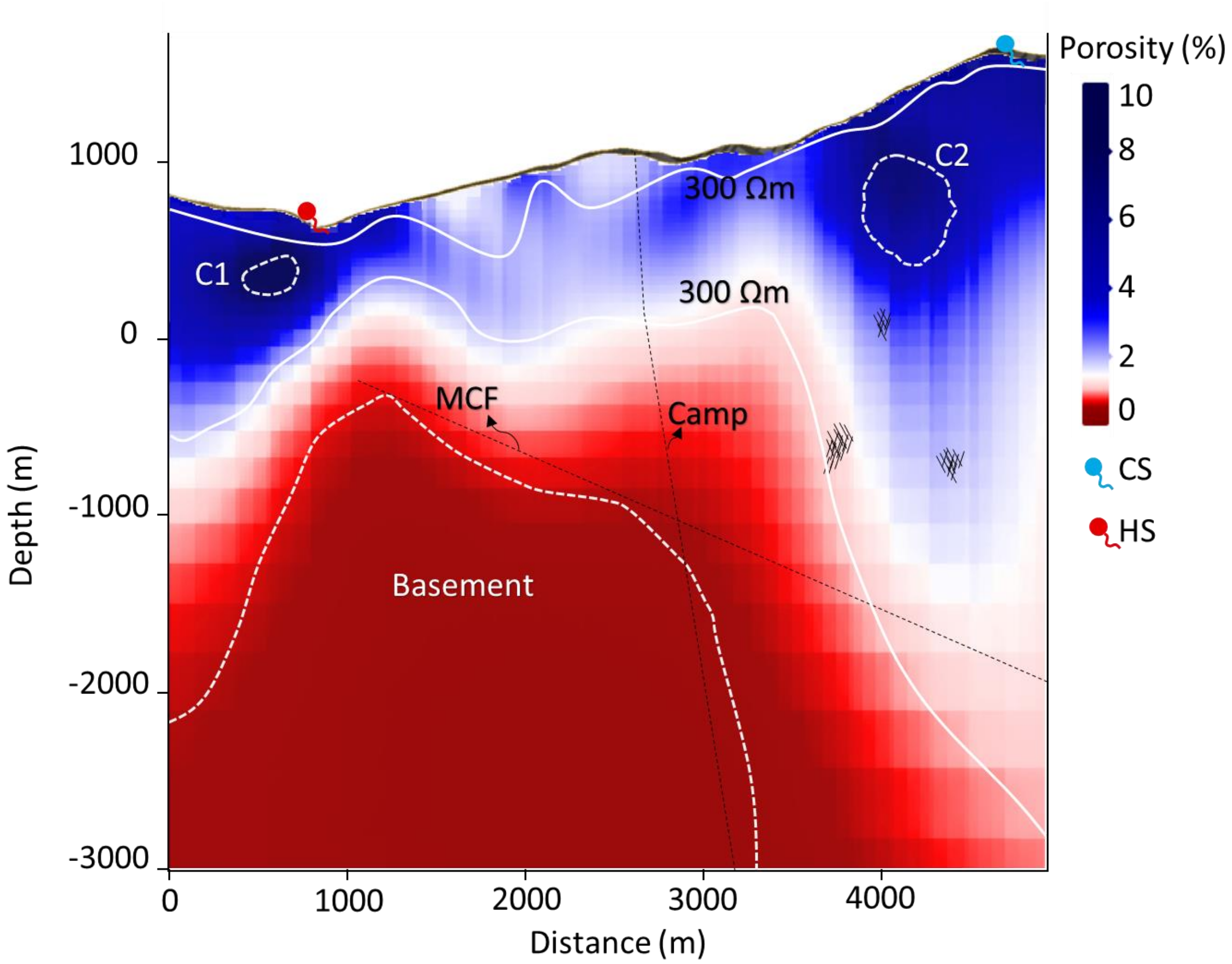
Black lines show different fluid resistivities with the fluid resistivity values annotating the lines.

We considered: $m = 1.6$ ⇨ φ = 0.1 – 8.5 %

Petrophysical Model

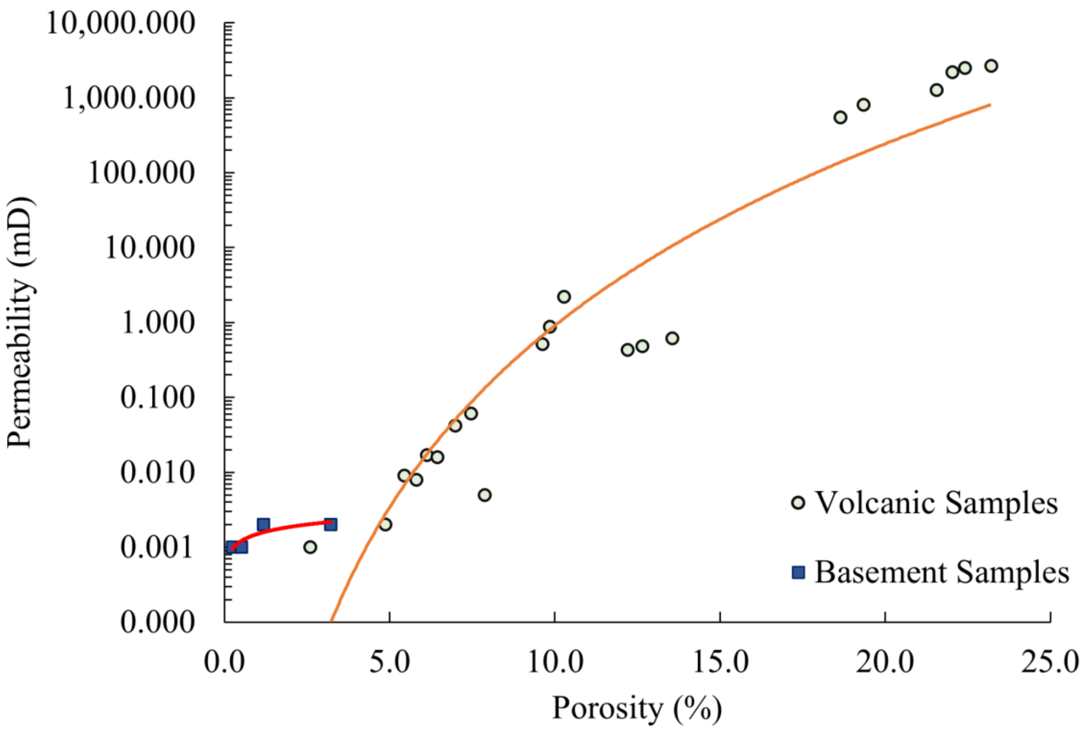
3-D Model of Porosity

- Bulk resistivities from the AMT model
- Fluid resistivity
- Temperature data



Petrophysical Model

Laboratory Tests



Basement samples:

- Permeability: Up to 0.002 md
- Porosity: 0.2–3.2 %

Volcanic samples:

- Permeability: 0.001–5,186.57 mD
- Porosity: 2.6–23.2 %

$$k_{volcanic} = 8 \times 10^{-9} \times \varphi^{8.0624}$$
$$k_{basement} = 0.0015 \times \varphi^{0.3181}$$

Parameter	HS^{+}	MAL
Porosity (%)	0.1–2.9	0.8–8.5
Permeability (mD)	0–0.002	0.001–0.249

Petrophysical Model

Fracture Porosity

Fracture set	Spacing (m)	Aperture (mm)
1	0.1 – 1	Tight – 20
2	0.1 – 1	Tight – 20
3	0.4 – 2	Tight
4	0.05 – 2	Tight – 5

Fracture set 2:

- NW-SE fracture direction
- Parallel to the regional stress direction
- Permeability up to 666 mD

Parameter	Modeling
Porosity (%)	0.02 – 40
Permeability (mD)	0.005–666

Building a Conceptual Model

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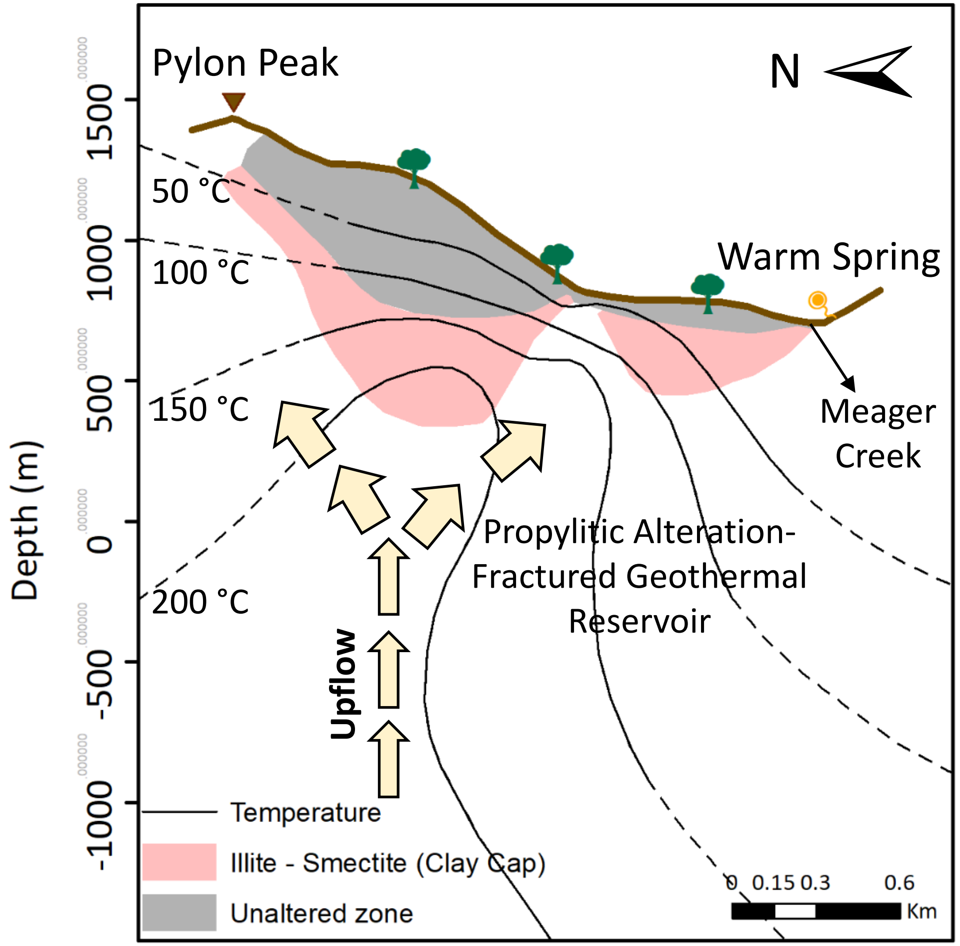

(Not to scale)

Conclusions

- The structures controlling the near surface conductor: No-Good and Meager Creek Faults.
- Components of Archie's law are defined for the study area.
- The zone related to 40–300 Ωm electrical resistivity:
    - Porosity: 0.1–8.5% and Permeability: 0.00–0.249 mD.
- The volcanic rocks showed higher permeability in laboratory measurements than fractured basement rock.
- Considering the pattern of fracture sets for drilling purposes will increase the permeability up to 666 mD.

Acknowledgements

- **Thanks to my Ph.D. supervisors, Jim Craven and Dariush Motazedian.**
- Steve Grasby for supervising Garibaldi Geothermal Volcanic Belt Assessment Project.
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References

- Archie, G. E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. 146 (1), 54–67.
- Darnet, M., Wawrzyniak, P., Coppo, N., Nielsson, S., Schill, E., Fridleifsson, G., 2020. Monitoring geothermal reservoir developments with the controlled-source electromagnetic method—A calibration study on the reykjanes geothermal field. J. Vol. Geotherm. Res., 391, 106437.
- Fairbank, B. D., Shore, G. A., Werner, L. J., Nevin, A. E., Sadlier-Brown, T. L., 1979. Report on 1978 field work, Meager Creek Geothermal Area, upper Lillooet river, British Columbia. NSBG Ltd.
- Grasby, S.E., Allen, D.M., Bell, S., Chen, Z., Ferguson, G., Jessop, A., Kelman, M., Ko, M., Majorowicz, J., Moore, M., Raymond, J., Therrien, R., 2012. Geothermal Energy Resource Potential of Canada. GEOLOGICAL SURVEY OF CANADA OPEN FILE 6914. 322 pages.
- How Does Geothermal Energy Work? - GreenFire Energy Inc.
- Hersir, G.P., Arnason, K., Vilhjalmsson, A.M., Sæmundsson, K., Agústsdottir, Þ., Frioleifsson, G. O., 2020. Krýsuvík high temperature geothermal area in SW Iceland: geological setting and 3D inversion of magnetotelluric (MT) resistivity data. J. Vol. Geotherm. Res., 391, 106500.
- Moeck, I. S., 2014. Catalog of geothermal play types based on geologic controls. Renewable and Sustainable Energy Reviews. 37, 867-882.
- Palacky, G. J., 1988. 3. Resistivity Characteristics of Geologic Targets. Investigations in Geophysics, 52–129.
- Pellerin, L., Johnston, J. M., Hohmann, G. W., 1996. A numerical evaluation of electromagnetic methods in geothermal exploration. Geophysics, 61 (1).
- Proenza, Y., 2012. Geothermal data compilation and analysis of alterra power's upper Lillooet property project course instructors. 2017-006 - Geoscience BC.
- Read, P. B., 1990. Mount Meager complex, Garibaldi Belt, southwestern British Columbia. Geoscience Canada, 17.
- ThinkGeoEnergy's Top 10 Geothermal Countries 2022 – installed power generation capacity (MWe)
- Ussher, G., Harvey, C., Johnstone, R., Anderson, E., 2000. Understanding the resistivities observed in geothermal systems. Proceedings World Geothermal Congress 2000, 1915–1920.

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